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# Comparison of Two Methods for Estimating Base Flow in Selected Reaches of the South Platte River, Colorado

Scientific Investigations Report 2012–5034

**U.S. Department of the Interior**
**U.S. Geological Survey**

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By Joseph P. Capesius and L. Rick Arnold

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**U.S. Department of the Interior**
**U.S. Geological Survey**

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# Conversion Factors and Datum

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Volume | |
| acre-foot (acre-ft) | 1,233 | cubic meter ($m^3$) |
| | Flow rate | |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| cubic foot per second per square mile [$(ft^3/s)/mi^2$] | 0.01093 | cubic meter per second per square kilometer [$(m^3/s)/km^2$] |

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F–32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Elevation, as used in this report, refers to distance above the vertical datum.

# Comparison of Two Methods for Estimating Base Flow in Selected Reaches of the South Platte River, Colorado

By Joseph P. Capesius and L. Rick Arnold


## Abstract

The U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board, compared two methods for estimating base flow in three reaches of the South Platte River between Denver and Kersey, Colorado. The two methods compared in this study are the Mass Balance and the Pilot Point methods. Base-flow estimates made with the two methods were based upon a 54-year period of record (1950 to 2003).

The Mass Balance method for estimating base flow is based on a mass balance of all known inflows to and outflows from a given stream reach, with the equation being solved for groundwater flow into or out of the reach. A positive mass balance indicates a gaining reach (base flow) and a negative balance indicates a losing reach. The mass balance was calculated using daily mean streamflow, wastewater treatment plant discharge, and stream diversion data. Monthly mean base flow was calculated as the average of all daily mean mass-balance results for a given month.

The Pilot Point method is based on a daily mean mass balance of all inflows to and outflows from a stream reach. The Pilot Point differs from the Mass Balance method in that extreme daily mass-balance results are constrained utilizing two analytical solutions that represent the maximum possible streamflow gain or loss. Additionally, the Pilot Point method utilizes a smoothing function, based on a moving average of the daily constrained mass-balance results. The moving average for this study utilized a moving-average period, called the bin width, of 61 days. The maximum and minimum base-flow constraints and the smoothing function are utilized to provide base-flow estimates that exhibit reasonable maximum values and temporal variability consistent with the concept of groundwater flow being gradual and slow.

Both the Mass Balance and Pilot Point results provided similar patterns in annual and monthly base flow. All three reaches were indicated to be gaining reaches, particularly after about 1970, with the magnitude of base flow increasing downstream. This degree of similarity between the two methods was expected because both methods are based on a streamflow mass balance. The magnitude of estimates provided by the two methods was measurably different. The stream gains and losses estimated using the Mass Balance method were consistently more variable and of greater magnitude than those estimated using the Pilot Point method. In the Denver to Henderson reach, the median estimated annual mean base flow was 34.0 cubic feet per second ($ft^3/s$) using the Mass Balance method and was 39.1 $ft^3/s$ using the Pilot Point method. In the Henderson to Fort Lupton reach, the median estimated annual mean base flow was 50.0 $ft^3/s$ using the Mass Balance method and was 40.0 $ft^3/s$ using the Pilot Point method. In the Fort Lupton to Kersey reach, the median estimated annual mean base flow was 234 $ft^3/s$ using the Mass Balance method and was 214 $ft^3/s$ using the Pilot Point method.

The Mass Balance results were quite variable over time such that they appeared suspect with respect to the concept of groundwater flow as being gradual and slow. The large degree of variability in the day-to-day and month-to-month Mass Balance results is likely the result of many factors. These factors could include ungaged stream inflows or outflows, short-term streamflow losses to and gains from temporary bank storage, and any lag in streamflow accounting owing to streamflow lag time of flow within a reach. The Pilot Point time series results were much less variable than the Mass Balance results and extreme values were effectively constrained. Less day-to-day variability, smaller magnitude extreme values, and smoother transitions in base-flow estimates provided by the Pilot Point method are more consistent with a conceptual model of groundwater flow being gradual and slow. The Pilot Point method provided a better fit to the conceptual model of groundwater flow and appeared to provide reasonable estimates of base flow.


## Introduction

Base flow typically is defined as the groundwater contribution to streamflow. Unfortunately, base flow cannot easily be measured using direct methods and commonly is estimated by using any of a variety of methods (Hall, 1968; Nathan and McMahon, 1990; Tallaksen, 1995; and Smakhtin, 2001). The fundamental assumption underlying the various base-flow analysis methods is that base flow is totally composed of groundwater discharge. For many streams this assumption is not always correct. Base flow in streams can be affected by several anthropogenic influences including reservoir releases, wastewater-treatment plant discharge, or irrigation return flow, all of which can influence or even dominate the stream hydrograph during periods of low streamflow (Hall, 1968; Nathan and McMahon, 1990; Tallaksen, 1995). Over a shorter timeframe, base flow can be substantially affected by temporary bank storage, followed by short-term inflow of water to the stream from bank storage which is commonly measured in terms of the hours to days associated with the occurrence of high-flow events (Griffiths and Clausen, 1997). Additionally, streamflow diversions for agricultural, domestic, or industrial use can affect base flow in streams on a seasonal or longer-term basis. Due to these complexities inherent to the composition of a streamflow hydrograph, it is important that the overall water budget and management regime for a stream be considered in any analysis of base flow (Brodie and Hostetler, 2005).

The Colorado Water Conservation Board (CWCB) and the Colorado Division of Water Resources (CDWR) are developing a computerized Decision Support System (DSS) for each of the major river basins in Colorado (*http://cdss.state.co.us/DNN/default.aspx*). The DSS is a comprehensive, computerized system designed to provide governmental agencies, water users, and water managers with a tool for organizing, accessing, and evaluating a wide range of information and alternative strategies for managing water resources. Several DSSs have already been developed and a DSS for the South Platte River Basin is currently (2011) being developed. A necessary component of the South Platte DSS is the characterization of base flow. The U.S. Geological Survey (USGS), in cooperation with the CWCB, conducted this study to provide a comparison of two base-flow estimation methods in three selected reaches of the South Platte River in Colorado. One of the base-flow methods evaluated is the Mass Balance method and the other is the Pilot Point method, which the CWCB plans to use in the development of the South Platte River Basin DSS. In this report, the Pilot Point method is compared to the Mass Balance method of base-flow estimation.

## Purpose and Scope

This report provides comparisons of two methods for the estimation of base flow and presents base-flow estimates for three regulated reaches of the South Platte River from Denver to Kersey in north-central Colorado (fig. 1). Streamflow records for a 54-year period from 1950 to 2003 were used in the comparison of the base-flow methods. The two base-flow methods are the Mass Balance method and the Pilot Point method (Raymond Bennett, Colorado Division of Water Resources, written commun., 2003), both of which are based on mass balance of streamflow.

## Description of Study Area

The study area includes three main-stem reaches of the South Platte River between Denver and Kersey, Colorado (fig. 1). The climate of the study area is semiarid continental. Elevation ranges from about 4,580 to about 5,155 ft above NAVD 88. Mean annual precipitation ranges from 11 to 14 inches. Mean monthly temperatures range from 32ºF in the winter to 70°F in the summer (Robson, 1987).

The surficial geology of the study area is primarily Quaternary sediments that consist of alluvium, colluvium, and eolian deposits (Robson, 1987). Coarse-grained alluvial deposits along the main stem of the South Platte River and its tributaries form the productive South Platte River alluvial aquifer. This aquifer is an important source of water used for agricultural irrigation along the river and is referred to as the “alluvial aquifer” in this report.

The alluvial aquifer along the main stem of the South Platte River in the study area typically ranges in width from about 2 to 5 mi, being narrowest between Henderson and Fort Lupton and widest in the Denver metropolitan area (Hurr and others, 1972a and 1972b). The saturated thickness of the alluvial aquifer is about 20 ft at Henderson, about 40 ft at Fort Lupton, and as much as 100 ft in an area south of the river channel near Greeley. In general, groundwater in the alluvial aquifer flows toward the river and in a downstream direction, indicating the stream normally gains groundwater (base flow) in the downstream direction.

The South Platte River and most of its perennial tributaries originate in the mountainous area in the western one-quarter of the basin where much of the streamflow originates as snowmelt runoff. Downstream from its headwaters, the South Platte River flows through a series of water-supply and flood-control reservoirs upstream from the Denver metropolitan area. Additionally, the South Platte River receives effluent from wastewater-treatment plants in Denver, and water is diverted at multiple points for irrigation and storage, primarily for agricultural uses, along its course.

Three main-stem reaches of the South Platte River were used in this study for the comparison of the two base-flow estimation methods; each reach is bounded by a streamgage at the upstream and downstream ends of the reach. The three reaches are (1) the Denver to Henderson reach (South Platte River at Denver (PLADENCO) streamgage to the South Platte River at Henderson (PLAHENCO) streamgage), (2) the Henderson to Fort Lupton reach (South Platte River at Henderson streamgage to the South Platte River at Fort Lupton (06721000) streamgage), and (3) the Fort Lupton to Kersey reach (South Platte River at Fort Lupton streamgage to the South Platte River near Kersey (PLAKERCO) streamgage). The locations for the streamgages that define the end points of each reach are shown in figure 1. Straightline diagrams that display the locations of inflows to and diversions from the South Platte River in the study area have been developed by the State of Colorado (2008) in support of the DSS.

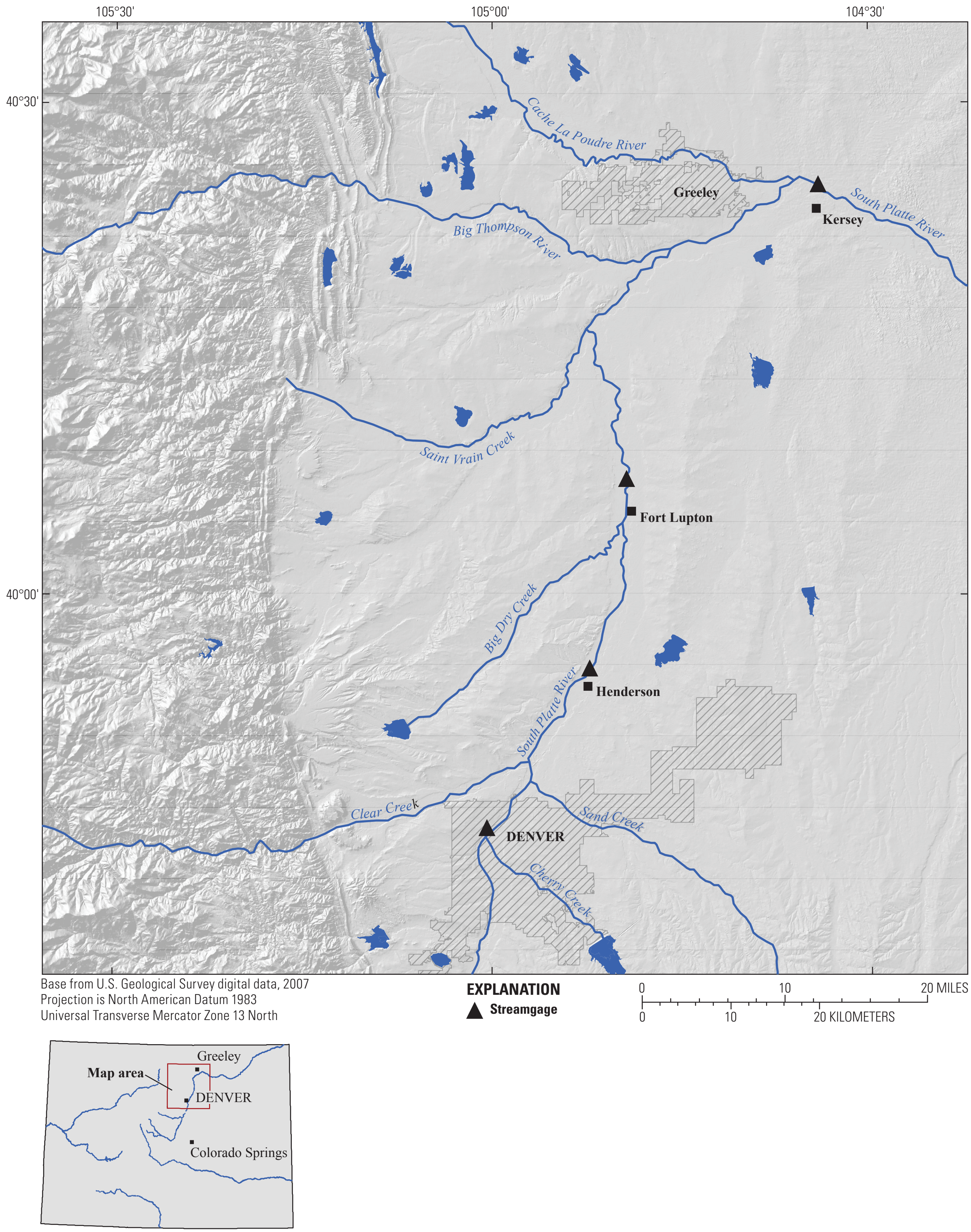


**Figure 1.** Map showing locations of study area and South Platte River streamgages utilized in the study.

The Denver to Henderson reach is approximately 15.6 mi long and begins in a heavily urbanized area of Denver. The reach contains two gaged tributary inflows and four gaged streamflow diversions (table 1). Flow in the Denver to Henderson reach of the South Platte River also is affected by releases from wastewater-treatment plants located upstream from and within the reach. The within-reach treatment plant, called the Metro Wastewater Reclamation District Central Treatment Plant, is located immediately upstream from the mouth of Sand Creek (fig. 1). Effluent from the Central Treatment Plant constitutes more than 90 percent of the flow in the reach during about 9 months of the year (Camp, Dresser, & McKee, 1994). Throughout much of the reach, channelization is prevalent (Camp, Dresser, & McKee, 1994). Downstream from Sand Creek, the low-flow channel is less confined, but the channel in this reach is flanked by numerous aggregate borrow pits that intercept the groundwater table and are used for water storage and other applications (Robson, 1996). Operation of actively mined aggregate pits in the Denver to Henderson reach, and in the other reaches studied, commonly requires pumping to remove groundwater that seeps into the pits and hinders access to the aggregate. The rate of dewatering for an individual pit is highly variable depending on the size and timeframe of the mining operation but typically is greater than 192,500 $ft^3/d$ (about 2 $ft^3/s$ ) (Arnold and others, 2010). Although some aggregate pits in the study area are permitted to discharge to the South Platte River (U.S. Environmental Protection Agency, 2010), the quantity of discharge from the pits generally is not formally documented. For this study, the discharge was assumed to be small compared to typical flows in the South Platte River and, therefore, was not considered in this base-flow analysis.

**Table 1.** Data stations used in the Mass Balance and Pilot Point method mass-balance computations.

[ID, identifier; USGS, U.S. Geological Survey; N/A, not applicable; WWTP, wastewater-treatment plant]

| Station name | Station ID | Station type | Data source |
|---|---|---|---|
| **Denver to Henderson Reach** | | | |
| Reach Inflows | | | |
| South Platte River at Denver | PLADENCO | Main stem | State of Colorado |
| Sand Creek at mouth near Commerce City | 394839104570300 | Tributary | USGS |
| Clear Creek at Derby | CLEDERCO | Tributary | State of Colorado |
| Metro Reclamation District WWTP | N/A | WWTP discharge | Denver Water Board |
| Reach Outflows | | | |
| South Platte River at Henderson | PLAHENCO | Main stem | State of Colorado |
| Fulton Ditch | 0200808 | Irrigation diversion | State of Colorado |
| Brantner Ditch | 0200809 | Irrigation diversion | State of Colorado |
| Burlington Ditch | 0200802 | Irrigation diversion | State of Colorado |
| Gardners Ditch | 0200806 | Irrigation diversion | State of Colorado |
| **Henderson to Fort Lupton Reach** | | | |
| Reach Inflows | | | |
| South Platte River at Henderson | PLAHENCO | Main stem | State of Colorado |
| Big Dry Creek at mouth near Fort Lupton | 06720990 | Tributary | USGS |
| Reach Outflows | | | |
| South Platte River at Fort Lupton | 06721000 | Main stem | USGS |
| Brighton Ditch | 0200810 | Irrigation diversion | State of Colorado |
| Lupton Bottom Ditch | 0200812 | Irrigation diversion | State of Colorado |
| Platteville Ditch | 0200813 | Irrigation diversion | State of Colorado |
| McCanne Ditch | 0200868 | Irrigation diversion | State of Colorado |
| **Fort Lupton to Kersey Reach** | | | |
| Reach Inflows | | | |
| South Platte River at Fort Lupton | 06721000 | Main stem | USGS |
| Saint Vrain Creek | SVCPLACO | Tributary | State of Colorado |
| Big Thompson River at mouth near LaSalle | 06744000 | Tributary | USGS |
| Cache la Poudre River | CLAGRECO | Tributary | State of Colorado |
| Reach Outflows | | | |
| South Platte River near Kersey | PLAKERCO | Main stem | State of Colorado |
| Beeman AKA Meadow Island #2 | 0200822 | Irrigation diversion | State of Colorado |
| Farmers Independent Ditch | 0200824 | Irrigation diversion | State of Colorado |
| Hewes Cook AKA Western Ditch | 0200825 | Irrigation diversion | State of Colorado |
| Jay Thomas Ditch | 0200826 | Irrigation diversion | State of Colorado |
| Union Ditch | 0200828 | Irrigation diversion | State of Colorado |
| Section 3 Ditch AKA Godfrey Bottom | 0200830 | Irrigation diversion | State of Colorado |
| Lower Latham Ditch | 0200834 | Irrigation diversion | State of Colorado |
| Patterson Ditch | 0200836 | Irrigation diversion | State of Colorado |
| Highland or Plum Ditch | 0200837 | Irrigation diversion | State of Colorado |
| Evans #2 Ditch | 0200817 | Irrigation diversion | State of Colorado |

The Henderson to Fort Lupton reach is 16.1 mi long. The reach contains one gaged tributary inflow and four gaged streamflow diversions (table 1). The South Platte River channel in this reach is more sinuous than the Denver to Henderson reach and has noticeable fluvial landforms such as point bars and a flood plain.

The Fort Lupton to Kersey reach is 36.6 mi long. The reach contains 3 gaged tributary inflows and 10 gaged streamflow diversions (table 1). The stream channel in this reach is sinuous, and a well-established riparian forest exists in many abandoned-channel areas along its course.

## Previous Investigations

Several previous investigations specifically examined the interaction of groundwater and surface water along the main stem of the South Platte River. The first studies by Carpenter (1916) and Parshall (1922) documented that agricultural irrigation increased the groundwater levels in the alluvial aquifer such that all reaches of the South Platte River became perennial. Parshall (1922) estimated that the South Platte River reach from Kersey to Julesburg had a mean gain of 751 $ft^3/s$ or about 5.3 $ft^3/s/mi$. Parshall (1922) also estimated, on the basis of records from three reservoirs, that seepage losses from reservoirs accounted for about 20 percent of all return flows.

Minges (1982) used a mass-balance approach to estimate streamflow gains and losses for a 25.8-mi reach of the river downstream from Greeley. The study determined that this reach of river had a mean gain of 143 $ft^3/s$ (5.5 $ft^3/s/mi$) from groundwater during 1977 to 1979. Minges (1982) also noted that the thicker the alluvial aquifer, the greater the opportunity for the river to gain or lose flow. A later study by Ruddy (1984) continued parts of the work conducted by Minges (1982) and calculated gains in streamflow of comparable magnitude in the reach. Ruddy (1984) reported that this reach of the South Platte River had an average downstream gain of 150 $ft^3/s$ during the irrigation season.

McMahon and others (1995) examined the quantity and quality of groundwater discharge in three reaches of the South Platte River from Denver to Fort Lupton. The study characterized base flow using two methods. The first method used episodic collections of instantaneous streamflow measurements at several locations during 1992 and 1993 to make mass-balance calculations. The second method used measurements of groundwater levels in 30 cross sections through the study reach and hydraulic methods to estimate the amount of groundwater movement through the sediment-water interface near the river. The mass-balance results indicated that the three reaches of the South Platte River had a median gain of 4.6 $ft^3/s/mi$, with results ranging from –27 $ft^3/s/mi$ (losing reach) to 17 $ft^3/s/mi$ (gaining reach) and that groundwater flow accounted for about 13 percent of the water in the river during the study period. The results from the groundwater-level measurements were considered to be representative of transient conditions that occur only in a small area in the vicinity of the river; the methods indicated movement of –1,360 to 1,000 $ft^3/s/mi$, with a median value of –5.8 $ft^3/s/mi$. The study suggested that much of the variability observed in groundwater movement through the sediment-water interface likely is due to the variations in the amount of effluent being discharged from wastewater-treatment plants in the Denver metropolitan area, which causes frequent changes to the water-surface elevation in the river and hydraulic-head differences between the river and alluvial aquifer.

# Methods

Methods are presented for data compilation and base-flow estimation. The two base-flow estimation methods used in the study are the Mass Balance method and the Pilot Point method.

## Data Compilation

Base flow of the three main-stem South Platte River reaches was analyzed using streamflow and stream diversion data collected by the USGS (2007) or State of Colorado (2007) (table 1). The Denver Water Board provided wastewater-treatment plant discharge data for the Metro Wastewater Reclamation District (Steve Schmitzer, Denver Water Board, written commun., 2005). The records of the daily mean streamflow for one main-stem streamgage and two tributary streamgages utilized in the study contained data gaps. Missing data were estimated for these gages so that the records were continuous for a 54-year period beginning in 1950, thus providing a common long-term period of record for the base-flow analysis. The South Platte River at Fort Lupton (06721000) streamgage was discontinued from October 1996 to May 2003. The correlation coefficient between the daily mean streamflow for the upstream streamgage in the reach, South Platte River at Henderson (06720500), and streamflow at the Fort Lupton gage have a correlation coefficient of 0.9681, indicating a strong correlation (Helsel and Hirsch, 1992). Missing flow data for the Fort Lupton gage were estimated using simple linear regression with flow data from the South Platte River at Henderson streamgage. The other two streamgages with missing data are the tributaries Sand Creek at mouth near Commerce City (394839104570300) and Big Dry Creek at mouth near Fort Lupton (06720990). Data collection at these two tributary sites began in October 1991 and February 1992, respectively, and continued through the end of the study period. Missing daily mean flow data for these two gages were estimated to be equal to the median monthly values of measured streamflow for the existing period of record, 1991–2003 and 1992–2003, respectively.

This method of estimating missing data introduces an additional source of error and uncertainty to the base-flow analysis; however, because both streams each represent less than 10 percent of the annual discharge of the main-stem reach to which they are tributary, the effect of the uncertainty is believed to be relatively minor.

## Base-Flow Estimation

Both the Mass Balance and Pilot Point methods for base-flow estimation are based on a mass-balance computation and should be reasonably robust to the effects of streamflow regulation and other anthropogenic effects on streamflow, provided that all substantial sources of inflow to and outflow from the stream are accurately measured and included in the mass-balance computation. The two methods are described in the following sections.

### Mass Balance Method

The Mass Balance method for estimating base flow is based on a mass balance of surface-water and groundwater inflows and outflows for a given stream reach, using the following equation:

$$Q_{in} + Q_{trib} + Q_{wwtp} + GW = Q_{div} + Q_{out} \qquad (1)$$

where

$Q_{in}$ = main-stem surface-water inflow to the reach,
$Q_{trib}$ = tributary surface-water inflow to the reach,
$Q_{wwtp}$ = municipal wastewater treatment plant discharge to the stream,
$GW$ = net groundwater inflow to or groundwater outflow from the stream,
$Q_{div}$ = streamflow diversions to ditches or canals,

and

$Q_{out}$ = main-stem surface-water outflow from the reach.

Equation 1 can be rearranged and solved for the groundwater component of flow:

$$GW = Q_{div} + Q_{out} - (Q_{in} + Q_{trib} + Q_{wwtp}) \qquad (2)$$

A positive groundwater component is indicative of a gaining stream due to groundwater flow into the stream reach (base flow). A negative groundwater component indicates a losing stream reach and recharge to the alluvial aquifer from the stream.

Although the mass-balance approach is relatively simplistic, it requires that all surface-water inflows and outflows in a stream reach are measured and used in the mass-balance, which can be a limiting factor. It was assumed in this study that all major sources of inflow to and outflow from the three study reaches were measured and included in the data used in the mass-balance computation (table 1). Almost certainly, some inflows and outflows in the three study reaches were not measured and accounted for, which would contribute to inaccuracy in the Mass Balance method; however, given the magnitude of the major, measured inflows and outflows relative to any potential unmeasured flows, the effect of any unmeasured flows on the estimation of base flow cannot be quantified but is believed to be relatively small.

In the initial mass-balance computations, daily mean streamflow data were used. The daily mass-balance results included substantial day-to-day variability, commonly exhibiting large reversals from positive to negative values and vice versa over a period of consecutive days (fig. 2). The short-term, dramatic variability in daily mass balances likely is not reflective of actual groundwater-surface water interactions, given the relatively slow movement of groundwater flow. This large variability in daily mass-balance results is most likely caused by unmeasured and unaccounted for stream inflows or outflows, short-term streamflow losses to and gains from temporary bank storage, and lag in streamflow accounting owing to lag time of flow within the reach. To develop base-flow estimates that are more reflective of actual groundwater-surface water interaction, the final mass balances used in this study for the Mass Balance method were computed with monthly mean streamflow values rather than daily values (fig. 2). The mass-balance results obtained using monthly mean streamflow data tended to smooth the estimates of groundwater-surface water interaction and are considered more reasonable estimates of base flow.

### Pilot Point Method

The Pilot Point method, like the Mass Balance method, is based on a reach-scale mass balance of surface-water and groundwater inflows and outflows (Ray Bennett, Colorado Division of Water Resources, written commun., 2003); however, the Pilot Point mass balance is computed on a daily time step and includes procedures to constrain extreme daily mass-balance results and smooth the constrained mass-balance results. The extreme-value constraints establish maximum allowable gains or losses. The Pilot Point method imparts those constraints on the results of the daily mass balances, thus eliminating unreasonably large streamflow gains or losses from the mass-balance results. The large gains and losses, which can vary greatly on a day-to-day basis, are not considered to be indicative of surface-water groundwater interaction, given the typically slow movement of groundwater. As previously described in the “Mass Balance Method” section, this large variability in daily mass-balance results is likely caused by ungaged stream inflows or outflows, short-term streamflow losses to and gains from temporary bank storage, and a lag in streamflow accounting owing to

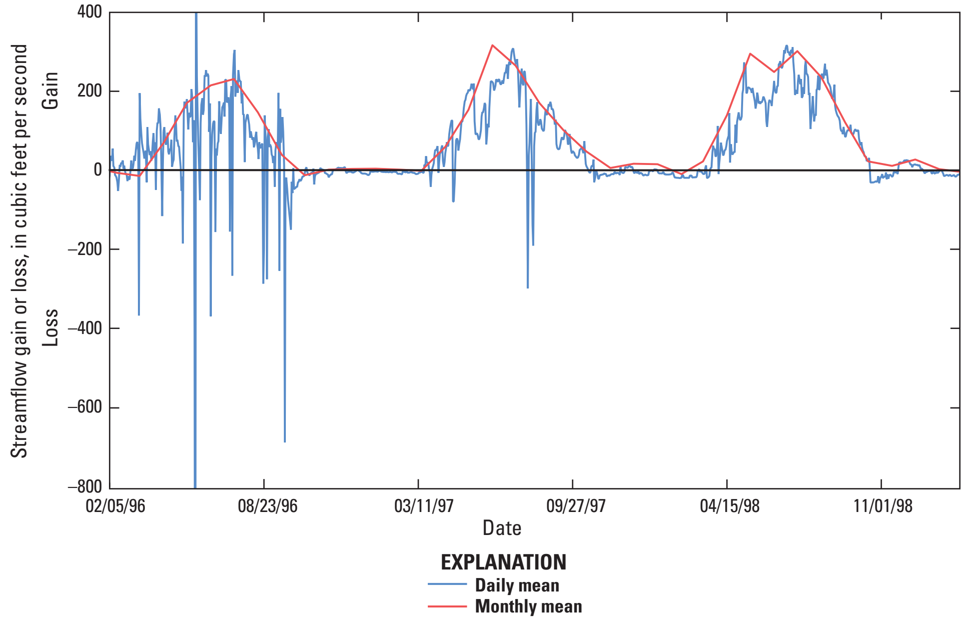


**Figure 2.** Comparison of streamflow gain and loss estimates based on daily mean and monthly mean Mass Balance method results, South Platte River,Henderson to Fort Lupton study reach, Colorado.

lag time of flow within a reach. Following application of the flow constraints, the Pilot Point method utilizes a smoothing technique to further reduce the large day-to-day variability in the constrained mass-balance results.

## Pilot Point Method Mass-Balance Constraints

Different analytical solutions are used to constrain extreme positive values (streamflow gains) and extreme negative values (streamflow losses) in the Pilot Point mass-balance results. An analytical solution using Darcy's law (Darcy, 1856) is used to constrain streamflow gains. Similarly, an analytical solution using the Glover equation (Glover, 1978) is used to constrain streamflow losses. Using the analytical solutions to constrain maximum streamflow gains and losses provides a quantitative and objective procedure for eliminating unreasonably large mass-balance results that likely are not indicative of actual groundwater-surface water interaction.

### Streamflow Gain Constraint

Because the South Platte River generally is a gaining stream in the study area, the maximum expected streamflow gain resulting from groundwater can reasonably be estimated using Darcy's law (Darcy, 1856). Darcy's law is an empirically derived equation that relates steady-state flow in a porous medium to hydraulic conductivity of the medium, hydraulic gradient, and cross-sectional area across which flow occurs and can be expressed as

$$Q = KA(dh/dl) \tag{3}$$

where

$Q$ is flow through cross-sectional area (A), in cubic feet per day,

$K$ is hydraulic conductivity, in feet per day,

$A$ is cross-sectional area, in square feet,

and

$dh/dl$ is hydraulic gradient, unitless.

Maximum expected streamflow gain was determined using Darcy's law with input values representative of hydrologic conditions within each river reach (table 2). Hydraulic conductivity, aquifer cross-sectional area, and hydraulic gradient were determined from maps and data presented in Hurr and others (1972a, 1972b); Robson (1996); Robson, Arnold, and Heiny (2000); Robson, Heiny, and Arnold (2000); and Wilson (1965). Because flows computed using Darcy's law represent gains to only one side of the stream, results were multiplied by a value between 1 and 2 to estimate total gains to both sides of the stream. A multiplier value less than 2 was used if the aquifer area on one side of the stream was substantially smaller than the other, thereby limiting gains on one side of the stream. The maximum computed streamflow gain (maximum gain constraint) ranged from 161 $ft^3/s$ for the Henderson to Fort Lupton reach to 451 $ft^3/s$ for the Fort Lupton to Kersey reach (table 2).

### Streamflow Loss Constraint

To represent maximum expected streamflow loss resulting from a short-term increase in river stage above the groundwater level in the surrounding aquifer and corresponding reversal of the stream-aquifer hydraulic gradient, Glover's equation 8–23 (Glover, 1978) was used in this study to calculate the maximum expected streamflow loss for each river reach. The Glover analytical solution treats the river as a parallel drain and can be used to quantify streamflow gains or losses, but is only used in the Pilot Point method to estimate the maximum streamflow loss. The Glover equation is based upon the difference in hydraulic head between the stream and aquifer, the duration of the difference, the area of the aquifer affected by the difference, and on aquifer properties and can be expressed as

$$Q = i\, L\, (1\text{-}P)\, X \tag{4}$$

where

$Q$ is the total gain or loss within the reach, in cubic feet per day,

$i$ is infiltration rate to the aquifer, in feet per day,

$L$ is the aquifer width, in feet,

$P$ is the ratio of aquifer volume yet to be drained to initial volume, presented in Glover (1978) as a function of $\alpha t/L^2$, in which $\alpha$ is an aquifer constant determined as aquifer transmissivity divided by specific yield, in square feet per day, and $t$ is the time since infiltration began, in days,

and

$X$ is the reach length, in feet.

The analytical solution is valid for groundwater systems that generally match the following assumptions:

- The aquifer is homogeneous;
- The aquifer base is a horizontal, no-flow boundary;
- Aquifer sides are parallel, vertical, no-flow boundaries;
- The stream fully penetrates the aquifer and is equidistant from and parallel to the aquifer sides;
- Groundwater flow is horizontal and perpendicular to the stream;
- The hydraulic gradient is equal to the slope of the water table;
- Infiltration represents a mean rate that is uniformly applied to the water table; and
- Groundwater density and viscosity are constant.

As part of the Rio Grande DSS, the difference between successive values of the 2-day moving average of flow computed using equation 4 was used as the basis for estimating streamflow loss, and the average of the differences computed for days 4–17 was found to effectively represent the maximum expected streamflow loss (Ray Bennett, Colorado Division of Water Resources, written commun., 2003). Therefore, the same method was used to estimate maximum expected streamflow loss from the South Platte River in this study.

The values of aquifer properties used in equation 4 to approximate maximum expected streamflow loss for each reach are given in table 3. Aquifer width and transmissivity were determined from various reports (Wilson, 1965; Hurr and others, 1972a, 1972b; Robson, 1996; Robson, Arnold, and Heiny, 2000; and Robson, Heiny, and Arnold, 2000). Specific yield was determined using typical values for unconsolidated alluvium composed of sand and gravel based on data presented in Johnson (1967). The value for infiltration rate (0.8 ft/d) used in approximating the maximum expected streamflow loss was set to a value sufficient to produce a rapid 4-ft rise in hydraulic head at the stream-aquifer interface, thereby simulating a 4-ft rise in stream stage and corresponding short-term reversal of the stream-aquifer hydraulic gradient resulting from sudden high-flow conditions. The maximum computed streamflow loss (maximum loss constraint) ranged from 93 $ft^3/s$ for the Henderson to Fort Lupton reach to 269 $ft^3/s$ for the Fort Lupton to Kersey reach (table 3).

### Data Smoothing

After extreme daily mass-balance results are constrained, the Pilot Point method uses a data smoothing technique to effectively reduce the remaining day-to-day variability. The data smoothing is accomplished with long-term averaging of

**Table 2.** Input values and final results for Pilot Point method maximum streamflow gain constraint.

| Parameter | Units | South Platte River Study Reach | | |
|---|---|---|---|---|
| | | Denver to Henderson | Henderson to Fort Lupton | Fort Lupton to Kersey |
| Hydraulic conductivity | Feet per day | 800 | 500 | 400 |
| Hydraulic gradient | Unitless | 0.007 | 0.005 | 0.004 |
| Reach length | Feet | 82,368 | 85,008 | 193,248 |
| Saturated thickness of alluvium at stream edge | Feet | 25 | 35 | 70 |
| Cross-sectional area | Square feet | 2,059,200 | 2,975,280 | 13,527,360 |
| Groundwater flow from 1 side of river | Cubic feet per second | 133 | 86 | 251 |
| Multiplier (weighting flow from 2 sides of river) | Unitless | 1.50 | 1.90 | 1.80 |
| Maximum streamflow gain constraint (groundwater flow from both sides of river) | Cubic feet per second | 200 | 161 | 451 |

the constrained daily mass balances. As part of the Rio Grande DSS, a 61-day moving average (30 days in the past plus the current day plus 30 days in the future) of the constrained daily-mean mass-balance was found, through trial and error, to effectively remove noise in the constrained values (Ray Bennett, Colorado Division of Water Resources, written commun., 2003). Therefore, the 61-day moving average was adopted for use in this study in estimating base flow by the Pilot Point method for the 3 reaches of the South Platte River.

## Comparison of Base-Flow Estimates

Base-flow estimates computed using the Mass Balance and Pilot Point methods are presented graphically for each of the three study reaches (figs. 3–11). The results are presented as annual mean base flow (figs. 3, 6, and 9), monthly mean base flow (figs. 4, 7, and 10), and mean monthly base flow (figs. 5, 8, and 11), respectively. In addition, statistical summaries of the annual and monthly mean base-flow estimates are presented in tables 4 and 5, respectively. Positive values of base flow are indicative of a gaining stream and negative values are indicative of a losing stream.

For the Denver to Henderson reach, both methods indicate the reach was a losing reach until about 1970 at which time it quickly transitioned to a gaining reach (fig. 3). The time series of estimated annual mean base flow for both methods (fig. 3) exhibit a distinct and dramatic step-like increase from a loss about 50 $ft^3/s$ or more to a gain of about 50 $ft^3/s$ or more within this reach around 1970. Available records indicate that discharge of treated wastewater from the Metro Wastewater Reclamation District increased from an average of about 69,000 acre-feet per year (95 $ft^3/s$) for the period 1947–66 to about 144,000 acre-feet per year (199 $ft^3/s$) for the period 1967–99 (Steve Schmitzer, Denver Water Board, written commun., 2005). The increase in effluent discharge is due, in part, to the consolidation of effluent discharge from many area wastewater treatment facilities to a single facility at the Metro plant (Frank, 2009). The general temporal pattern of the annual base-flow time series for the two methods is quite similar. The median annual mean base flow was estimated to be 34.0 $ft^3/s$ using the Mass Balance method and 39.1 $ft^3/s$ using the Pilot Point method (table 4). Expressed as streamflow gain per river mile, the Mass Balance estimate of annual mean base flow was 2.2 $ft^3/s/mi$ and the Pilot Point estimate was 2.5 $ft^3/s/mi$. The Mass Balance estimates were more variable and generally larger in magnitude than the Pilot Point estimates for 1950 through about 1969, the period that the reach was determined to be losing. After about 1969, the Mass Balance estimates were very similar to the Pilot Point estimates and both methods characterized the reach as a gaining reach after 1969 (fig. 3). The monthly mean base-flow estimates for the reach show similar temporal patterns to the annual estimates (fig. 4). The median monthly mean base flow was estimated to be 19.7 $ft^3/s$ using the Mass Balance method and 23.4 $ft^3/s$ using the Pilot Point method. The plots of mean monthly base flow provide additional information on the seasonality of the estimated base flow (fig. 5). Base-flow estimates for both methods were larger for the months of September through February than for March through August; however, the Mass Balance estimates indicate a losing reach during March through August and the Pilot Point method indicates a gaining reach through most of the year. A possible explanation for the seasonality in base flow is that streamflow in the reach tends to be considerably larger during the late spring and summer months largely due to snowmelt and rainfall runoff. The associated elevated stream stage during these months could either effectively flatten the gradient between the aquifer and stream, thus decreasing base flow, or be so large as to reverse the gradient, which would cause the stream to lose water to the alluvial aquifer.

**Table 3.** Input values and final results for Pilot Point method maximum streamflow loss constraint.

| Parameter | Units | South Platte River Study Reach: Denver to Henderson | Henderson to Fort Lupton | Fort Lupton to Kersey |
|---|---|---|---|---|
| Infiltration rate[1] | Feet per day | 0.80 | 0.80 | 0.80 |
| Transmissivity | Square feet per day | 20,000 | 17,500 | 28,000 |
| Specific yield | Unitless | 0.2 | 0.2 | 0.2 |
| Aquifer width | Feet | 14,000 | 14,000 | 17,000 |
| Time[2] | Days | 14 | 14 | 14 |
| Reach length | Feet | 82,368 | 85,008 | 193,248 |
| Aquifer constant[3] | Square feet per day | 100,000 | 87,500 | 140,000 |
| Maximum streamflow loss constraint[4] | Cubic feet per second | 97 | 93 | 269 |

[1]Infiltration rate represents a value sufficient to produce a rapid 4-ft rise in hydraulic head at the stream-aquifer interface; calculated as hydraulic-head rise multiplied by specific yield.

[2]Time represents the number of days since the rapid rise in hydraulic head occurred.

[3]Aquifer constant is calculated as transmissivity divided by specific yield.

[4]Maximum streamflow loss constraint estimated by (1) using Glover's equation 8–23 (Glover, 1978) to compute daily values of streamflow loss, (2) calculating the 2-day moving average of streamflow loss, (3) taking the difference between successive values of the 2-day moving average, and (4) averaging the differences between successive values for days 4–17.

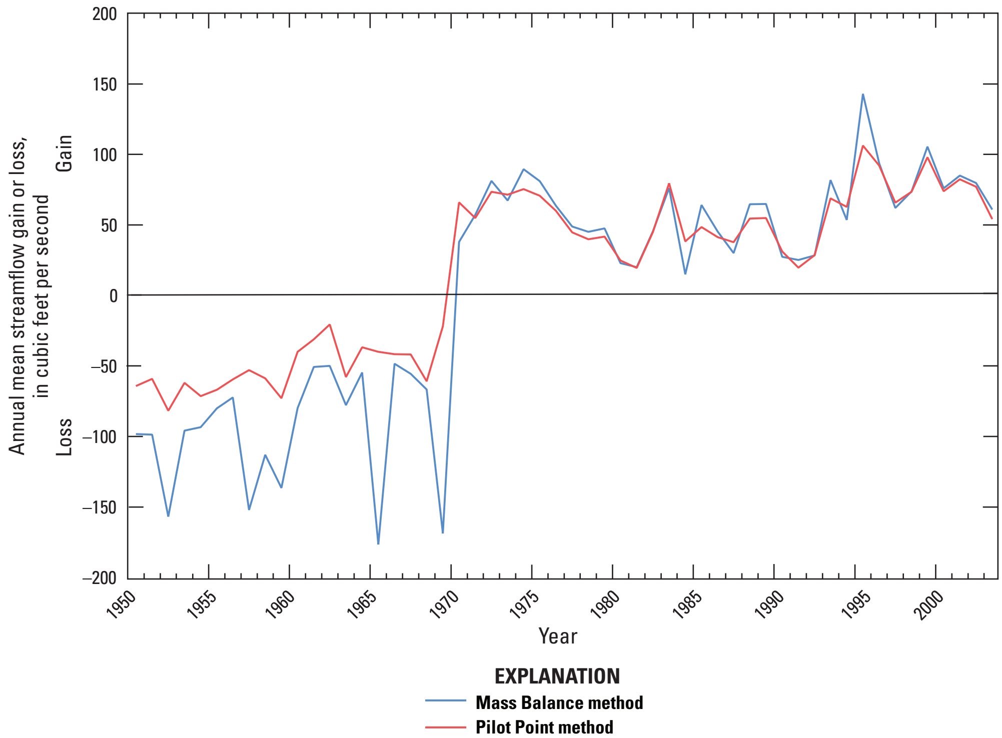


**Figure 3.** Comparison of annual mean streamflow gain and loss estimates for the South Platte River, Denver to Henderson study reach, Colorado.

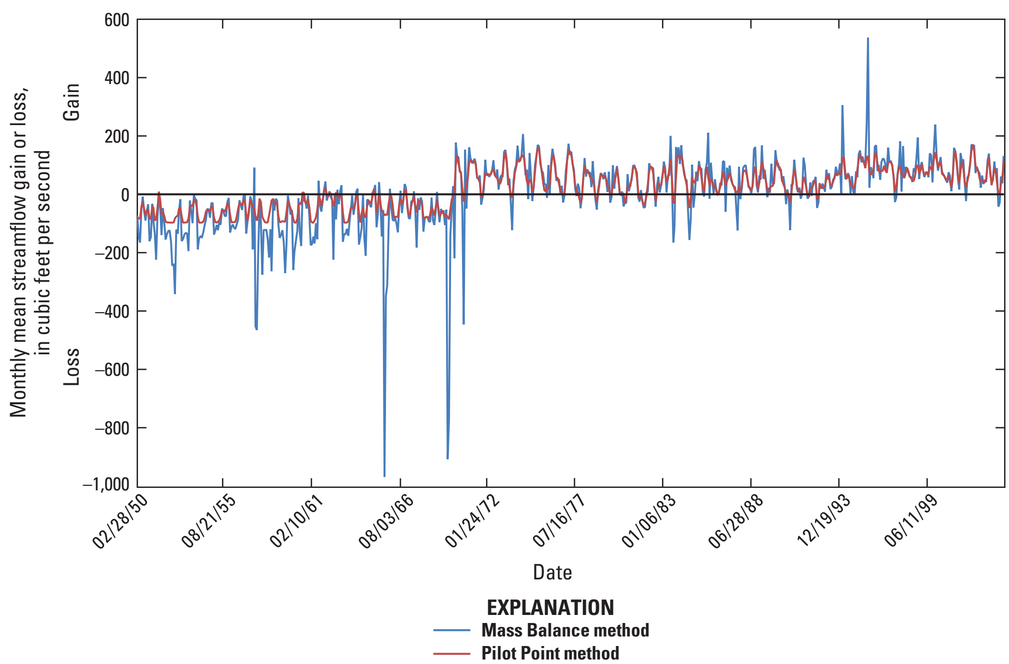


**Figure 4.** Comparison of monthly mean streamflow gain and loss estimates for the South Platte River, Denver to Henderson study reach, Colorado.

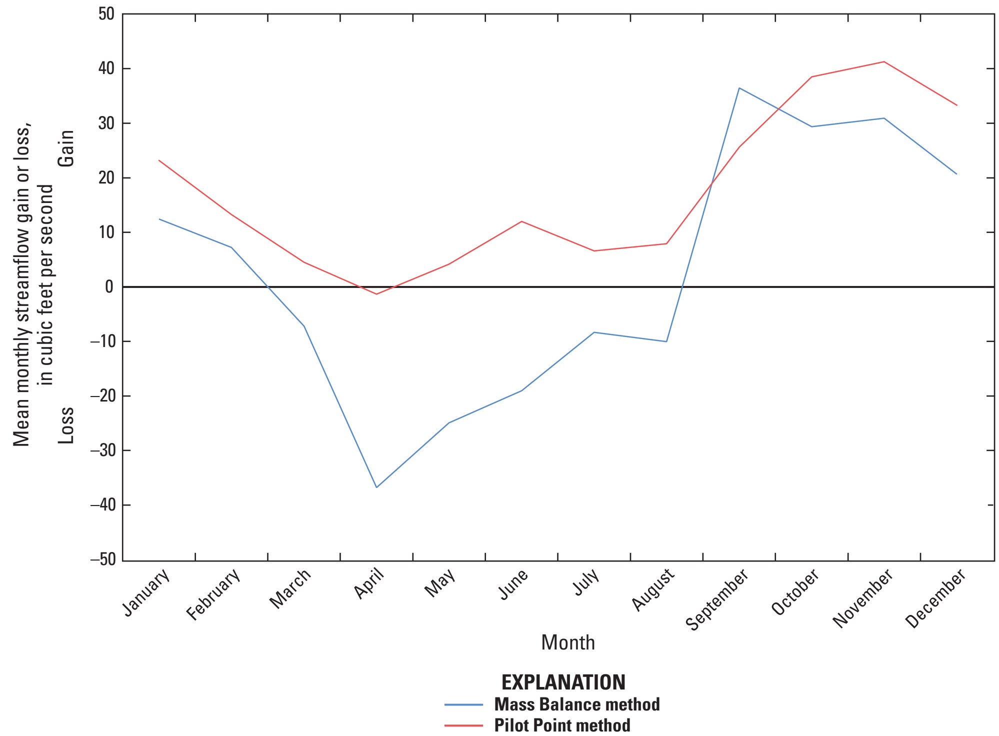


**Figure 5.** Comparison of mean monthly streamflow gain and loss estimates for the South Platte River, Denver to Henderson study reach, Colorado.

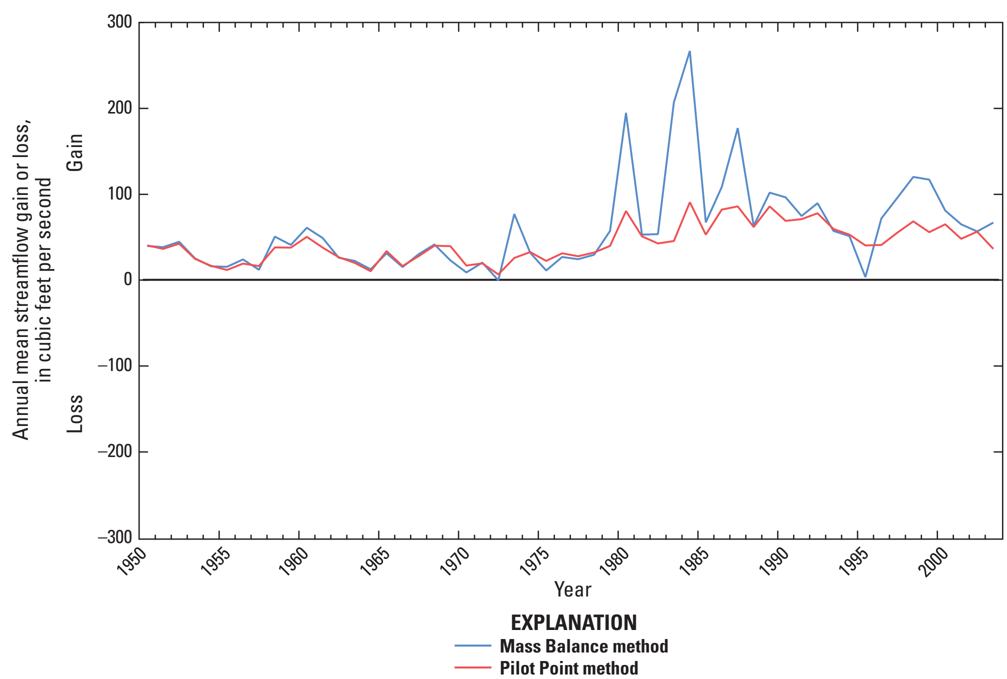


**Figure 6.** Comparison of annual mean streamflow gain and loss estimates for the South Platte River, Henderson to Fort Lupton study reach, Colorado.

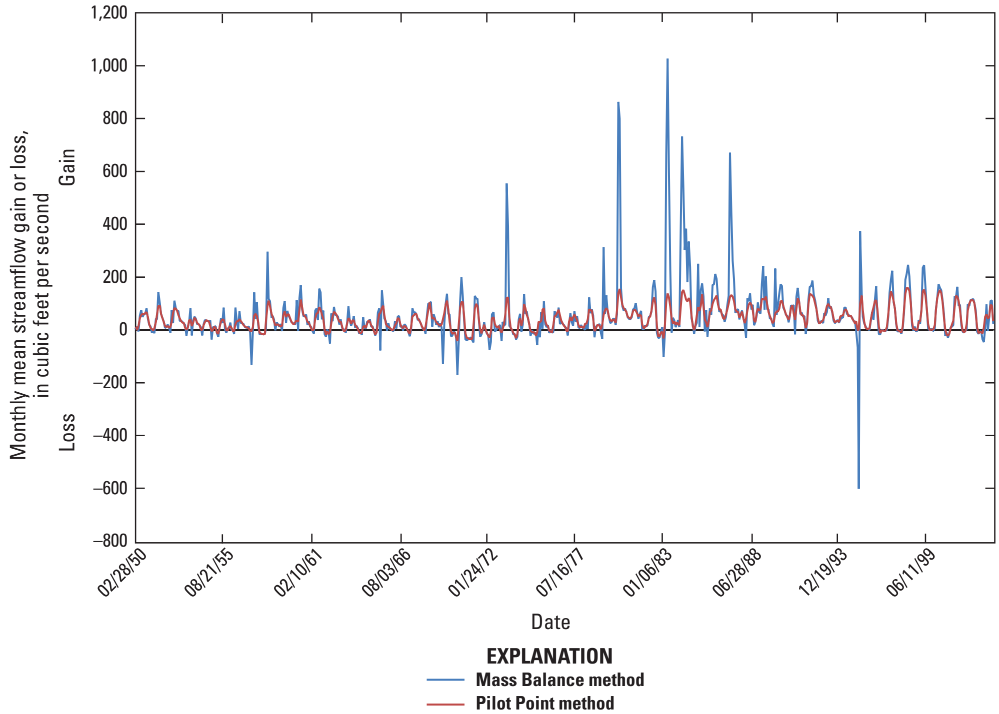


**Figure 7.** Comparison of monthly mean streamflow gain and loss estimates for the South Platte River, Henderson to Fort Lupton study reach, Colorado.

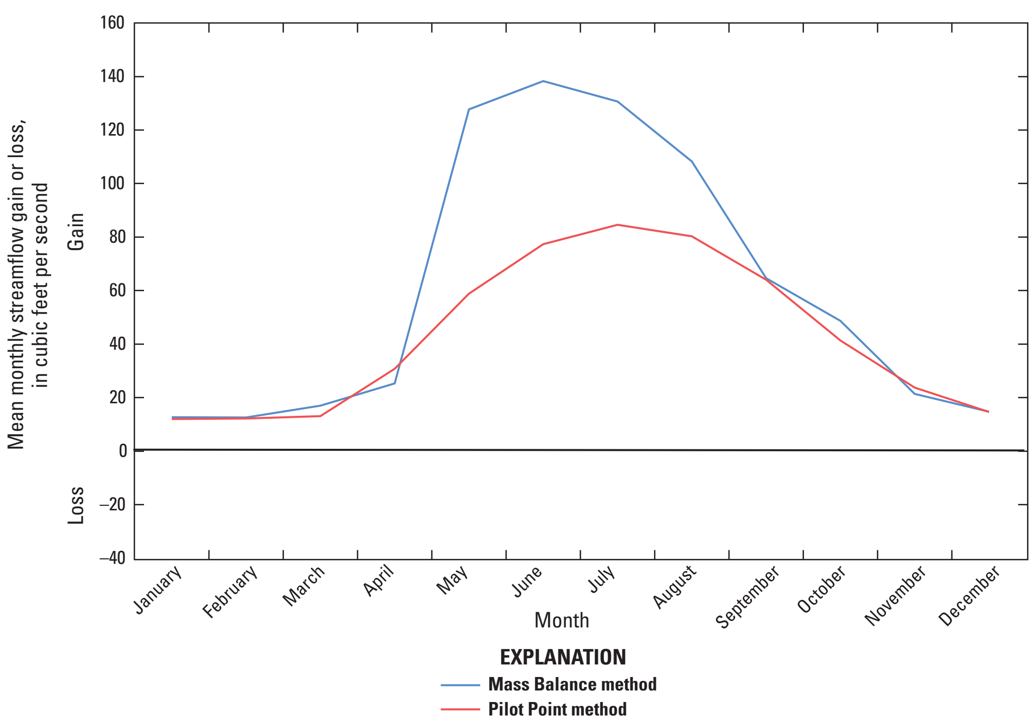


**Figure 8.** Comparison of mean monthly streamflow gain and loss estimates for the South Platte River, Henderson to Fort Lupton study reach, Colorado.

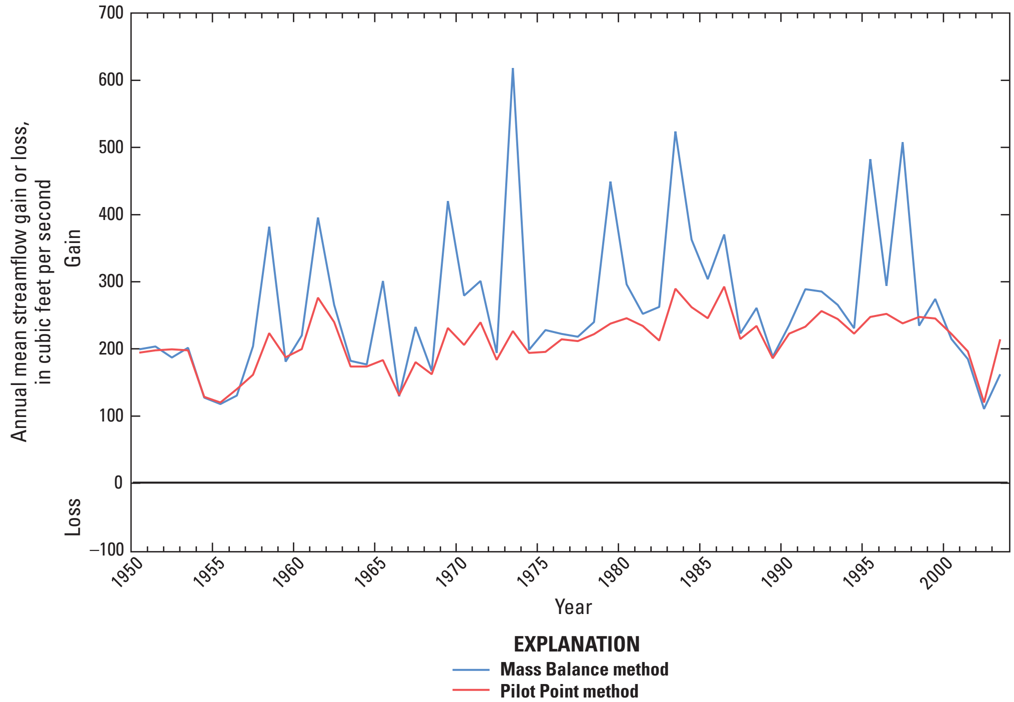


**Figure 9.** Comparison of annual mean streamflow gain and loss estimates for the South Platte River, Fort Lupton to Kersey study reach, Colorado.

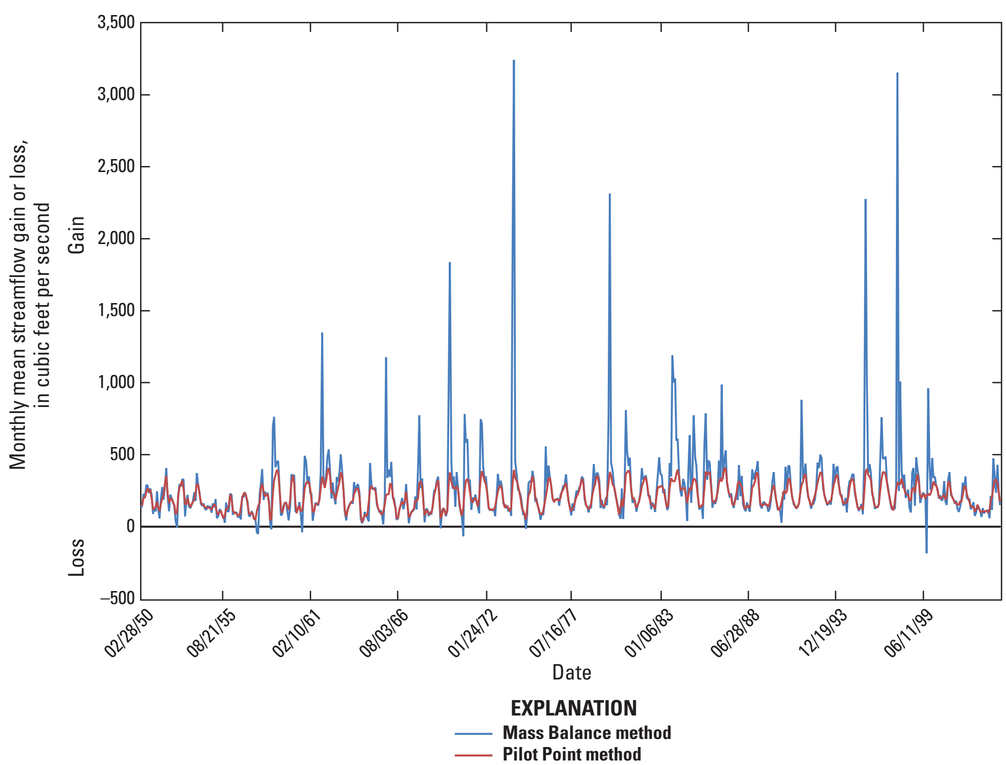


**Figure 10.** Comparison of monthly mean streamflow gain and loss estimates for the South Platte River, Fort Lupton to Kersey study reach, Colorado.

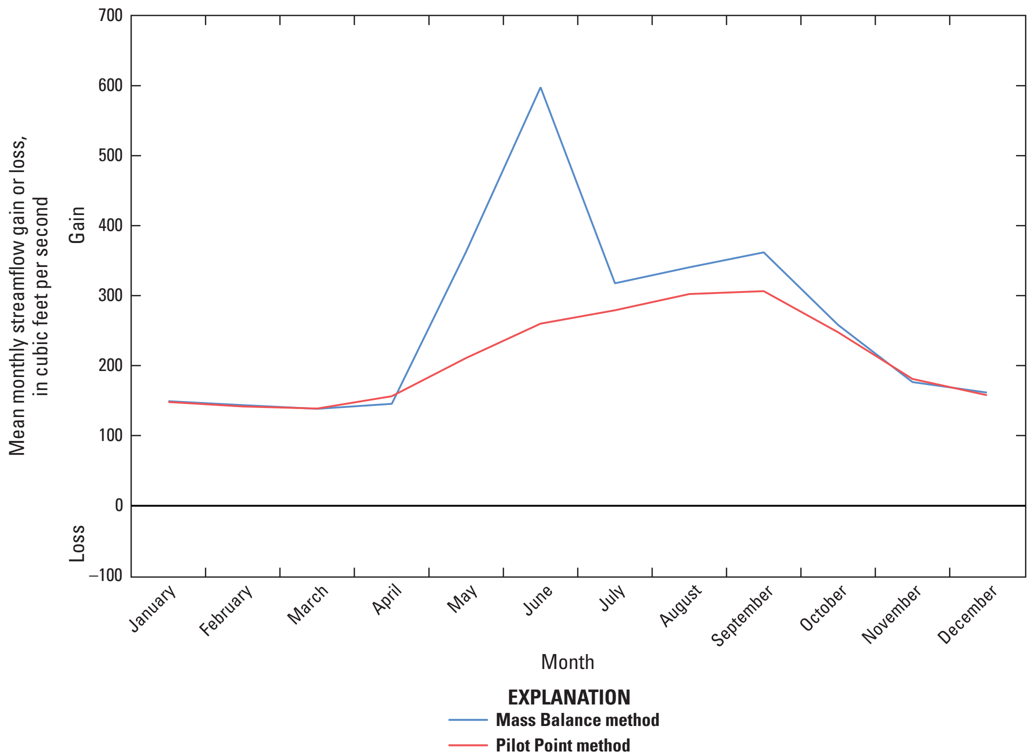


**Figure 11.** Comparison of mean monthly streamflow gain and loss estimates for the South Platte River, Fort Lupton to Kersey study reach, Colorado.

**Table 4.** Statistical summary of annual mean base-flow estimates using the Mass Balance and Pilot Point methods, South Platte River, Colorado, 1950–2003.

[$ft^3/s$, cubic feet per second]

| Statistic | Mass Balance method ($ft^3/s$) | Pilot Point method ($ft^3/s$) |
|---|---|---|
| Denver to Henderson Reach | | |
| Mean | 3.00 | 17.3 |
| Median | 34.0 | 39.1 |
| Minimum | –176 | –81.7 |
| Maximum | 143 | 106 |
| 25th percentile | –71.0 | –41.2 |
| 75th percentile | 65.0 | 65.9 |
| Henderson to Fort Lupton Reach | | |
| Mean | 60.0 | 43.0 |
| Median | 50.0 | 40.0 |
| Minimum | 0.00 | 6.80 |
| Maximum | 267 | 90.9 |
| 25th percentile | 25.0 | 27.0 |
| 75th percentile | 74.0 | 55.7 |
| Fort Lupton to Kersey Reach | | |
| Mean | 263 | 211 |
| Median | 234 | 214 |
| Minimum | 111 | 120 |
| Maximum | 618 | 293 |
| 25th percentile | 195 | 189 |
| 75th percentile | 296 | 239 |

For the Henderson to Fort Lupton reach, both methods indicate the reach was a gaining reach throughout the study period (fig. 6). Similar to the Denver to Henderson reach, the general temporal pattern of the annual mean base-flow time series for the two methods are similar during much of the study period up until about 1980. The Mass Balance annual mean base-flow estimates were more variable and generally larger in magnitude than the Pilot Point estimates during much of the study period after 1980. The median annual mean base flow was estimated to be 50.0 $ft^3/s$ using the Mass Balance method and 40.0 $ft^3/s$ using the Pilot Point method (table 4). Expressed as streamflow gain per river mile, the Mass Balance estimate of annual mean base flow was 3.1 $ft^3/s/mi$ and the Pilot Point estimate was 2.5 $ft^3/s/mi$. The monthly mean base-flow estimates for the reach show similar temporal patterns to the annual estimates (fig. 7). The median monthly mean base flow was estimated to be 32.9 $ft^3/s$ using the Mass Balance method and 35.4 $ft^3/s$ using the Pilot Point method. Seasonally, both methods indicated base flow to be considerably larger during the summer months than during the rest of the year (fig. 8), a different seasonal pattern than exhibited in the Denver to Henderson reach. This seasonal pattern is likely due to diversion of streamflow for agricultural irrigation, thus increasing the head in the alluvial aquifer and the gradient from the aquifer toward the stream. This situation

**Table 5.** Statistical summary of monthly mean base-flow estimates using the Mass Balance and Pilot Point methods, South Platte River, Colorado, 1950–2003.

[$ft^3/s$, cubic feet per second]

| Statistic | Mass Balance method ($ft^3/s$) | Pilot Point method ($ft^3/s$) |
|---|---|---|
| **Denver to Henderson Reach** | | |
| Mean | 3.70 | 17.4 |
| Median | 19.7 | 23.4 |
| Minimum | –969 | –96.7 |
| Maximum | 537 | 171 |
| 25th percentile | –51.8 | –37.0 |
| 75th percentile | 78.3 | 68.5 |
| **Henderson to Fort Lupton Reach** | | |
| Mean | 56.3 | 42.8 |
| Median | 32.9 | 35.4 |
| Minimum | –602 | –42.0 |
| Maximum | 1,023 | 159 |
| 25th percentile | 4.60 | 11.2 |
| 75th percentile | 76.8 | 72.0 |
| **Fort Lupton to Kersey Reach** | | |
| Mean | 264 | 211 |
| Median | 201 | 200 |
| Minimum | –185 | 30.3 |
| Maximum | 3,243 | 407 |
| 25th percentile | 130 | 141 |
| 75th percentile | 322 | 278 |

would tend to increase streamflow gains or base flow during the irrigation period (spring through summer) and up to a month or so after.

For the Fort Lupton to Kersey reach, both methods indicate the reach was a gaining reach throughout the study period (fig. 9). Similar to the two upstream study reaches, the general temporal patterns of the annual mean base-flow time series for the two methods are quite similar; however, the Mass Balance annual base-flow estimates were more variable and generally larger in magnitude than the Pilot Point estimates. The median annual mean base flow was estimated to be 234 $ft^3/s$ using the Mass Balance method and 214 $ft^3/s$ using the Pilot Point method (table 4). Expressed as streamflow gain per river mile, the Mass Balance estimate of annual mean base flow was 6.4 $ft^3/s/mi$ and the Pilot Point estimate was 5.8 $ft^3/s/mi$. The monthly mean base-flow estimates for the reach show similar temporal patterns to the annual estimates (fig. 10). The median monthly mean base flow was estimated to be 201 $ft^3/s$ using the Mass balance method and 200 $ft^3/s$ using the Pilot Point method. Seasonally, both methods indicated base flow to be considerably larger during the summer months than during the rest of the year (fig. 11), a seasonal pattern similar to that for the Henderson to Fort Lupton reach.

No direct measurements of base flow are available for comparison to the results from this study, but results from McMahon and others (1995) provide data for comparison that might best represent actual base-flow values. McMahon and others (1995) made a series of detailed gain-loss studies in two of the three reaches included in this study, carefully measuring all inflows to and outflows from the reaches and doing so with a Lagrangian longitudinal measurement design. Their approach established the timing of streamflow measurements relative to time-of-travel within each stream reach and minimized any effects of non-steady-state streamflow conditions. Although the measurement locations used by McMahon and others (1995) do not correspond exactly to the location of the downstream ends of the study reaches used in this report, they are reasonably located to allow for comparison between the results of McMahon and others (1995) and the current study. The measurements made by McMahon and others (1995) are compared to the results from this study in figure 12 for the Denver to Henderson reach and in figure 13 for the Henderson to Fort Lupton reach. The measurements made by McMahon and others (1995) were made during times coincident with times during the study period for which the Mass Balance and Pilot Point method results were nearly equivalent. For both reaches, the Mass Balance and Pilot Point estimates tend to compare reasonably well, with some exceptions, with results from McMahon and others (1995) (figs. 12 and 13). Neither study method exhibited a discernibly better fit with the measurements from McMahon and others (1995). It is interesting to note that for those instances in 1992 and 1993 in the Henderson to Fort Lupton reach when the study results did not compare well with McMahon and others (1995), both study methods compared reasonably well with one another. Assuming that McMahon and others (1995) accounted for all measureable inflows to and outflows from the river, it is possible that some of the inflows or outflows directly measured and used by McMahon and others (1995) were unaccounted for in the historical streamgage records used in the current study, thus providing a poor fit at times between the current study results and McMahon and others (1995). This situation reinforces the point that the accuracy of base-flow estimates based upon a mass-balance computation are highly dependent on all stream inflows and outflows being accurately measured and accounted for in the mass-balance computation.

These comparisons of the estimates from the Mass Balance and Pilot Point methods and the gain-loss measurements from McMahon and others (1995) provide some indication that both the Mass Balance and Pilot Point methods are capable of providing reasonable estimates of base flow; however, the comparisons do little to identify which method provides more accurate estimates of base flow. More insight into this issue might have been provided if historical measurements were available for times in the period of record when the Mass Balance and Pilot Point methods did not compare reasonably well with one another.

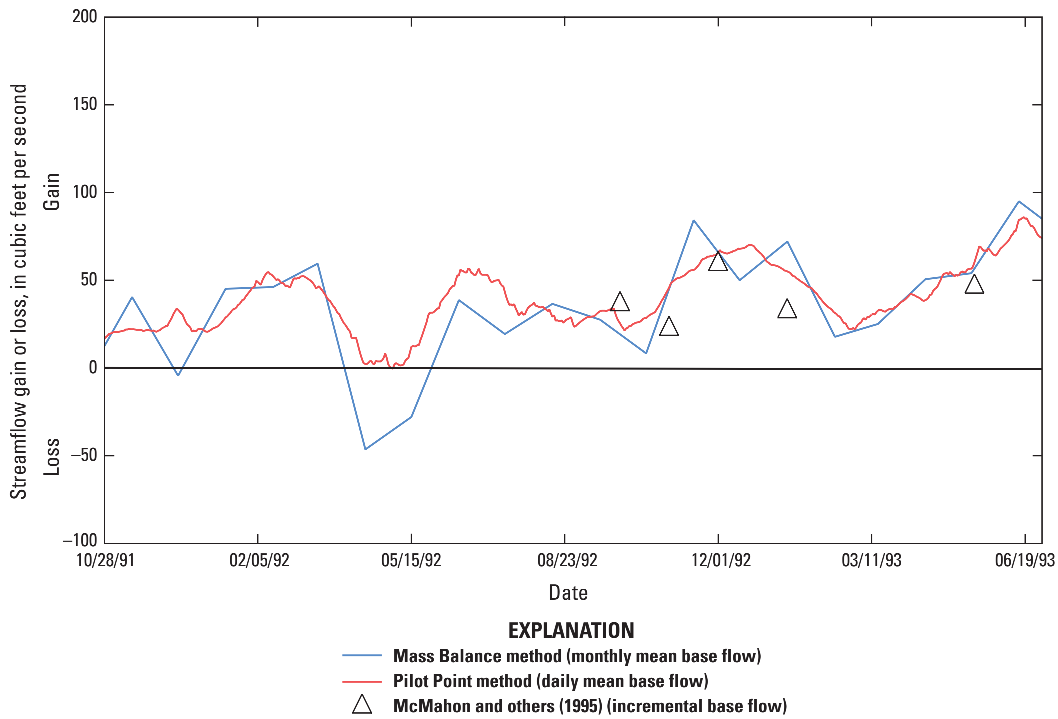


**Figure 12.** Comparison of streamflow gain and loss estimates from Mass Balance and Pilot Point methods with McMahon and others (1995), South Platte River, Denver to Henderson study reach, Colorado.

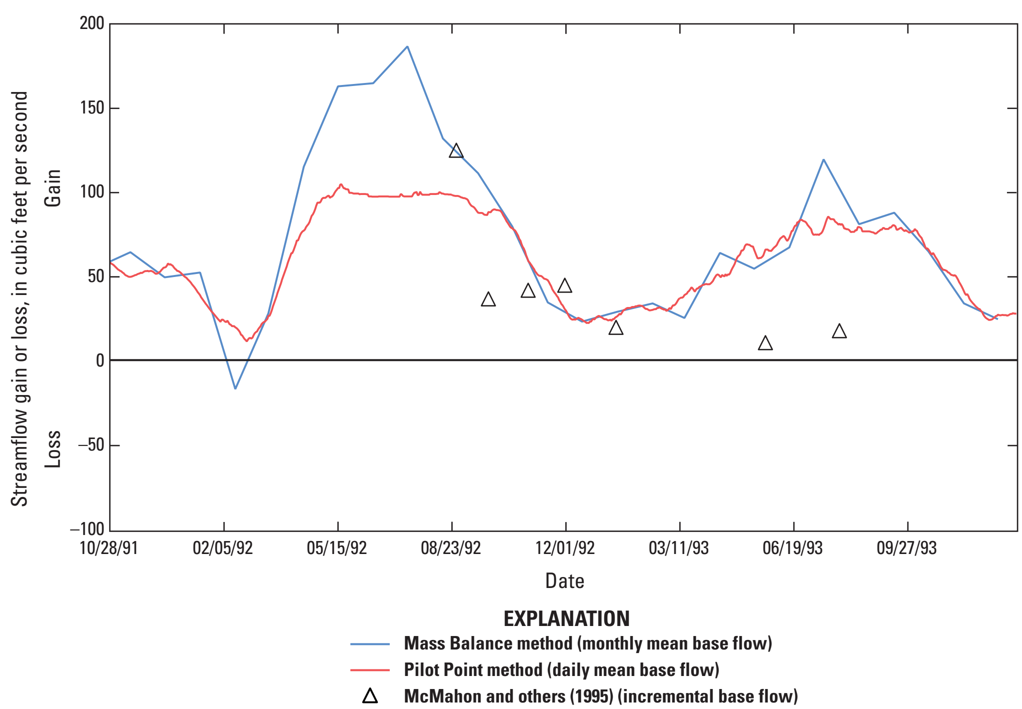


**Figure 13.** Comparison of streamflow gain and loss estimates from Mass Balance and Pilot Point methods with McMahon and others (1995), South Platte River, Henderson to Fort Lupton study reach, Colorado.

# Comparison of Mass Balance and Pilot Point Methods

The Mass Balance and Pilot Point methods for base-flow estimation are based on a mass balance of the same inflow and outflow data for a given reach. As a result, one would expect the estimates from the two methods to be similar, if not in magnitude, at least in general temporal patterns. For this study, both methods provided results that were very similar in terms of patterns in the annual and monthly time series. All three reaches were indicated to be gaining reaches, particularly after 1970, with the magnitude of base flow increasing downstream. In addition, both methods were in reasonably good agreement with the best available historical base-flow data for the study area during a period when both methods were in close agreement.

The Mass Balance method provided estimates of streamflow gains and losses that were more variable and of larger magnitude than those provided by the Pilot Point method. At times, and over the length of the study period, the Mass Balance results were so variable and large that they violated the concept of groundwater flow as being gradual and slow. In addition, the Pilot Point time-series results were much smoother in transition than the Mass Balance results (figs. 4, 7, and 10). The maximum streamflow gain and loss constraints and the data smoothing procedure utilized by the Pilot Point method effectively reduced the extreme base-flow estimates and large variability in base-flow estimates that are common in the results of the Mass Balance method. Boxplots of the annual mean and monthly mean base-flow estimates (figs. 14 and 15, respectively) clearly illustrate the effect of the maximum streamflow gain and loss constraints used by the Pilot Point Method. This large degree of variability in the day-to-day and month-to-month Mass Balance results is likely the result of factors other than streamflow gains from or losses to the alluvial aquifer. These factors could include ungaged stream inflows or outflows, short-term streamflow losses to and gains from temporary bank storage, and any lag in streamflow accounting owing to lag time of flow within a reach. Less day-to-day variability, smaller magnitude extreme values, and smoother transitions in base-flow estimates are

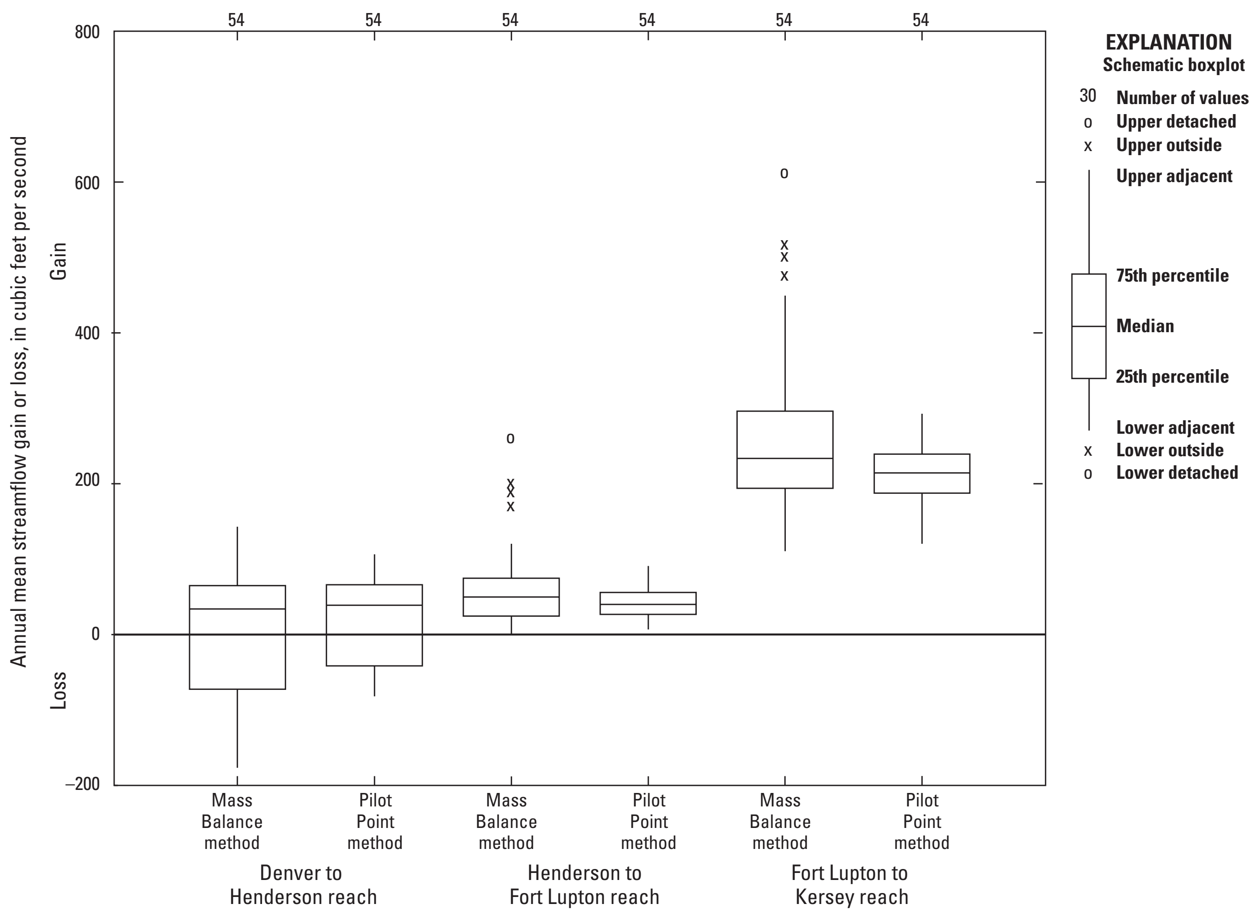


**Figure 14.** Boxplots comparing Mass Balance and Pilot Point estimates of annual mean streamflow gains and losses for South Platte River study reaches, Colorado.

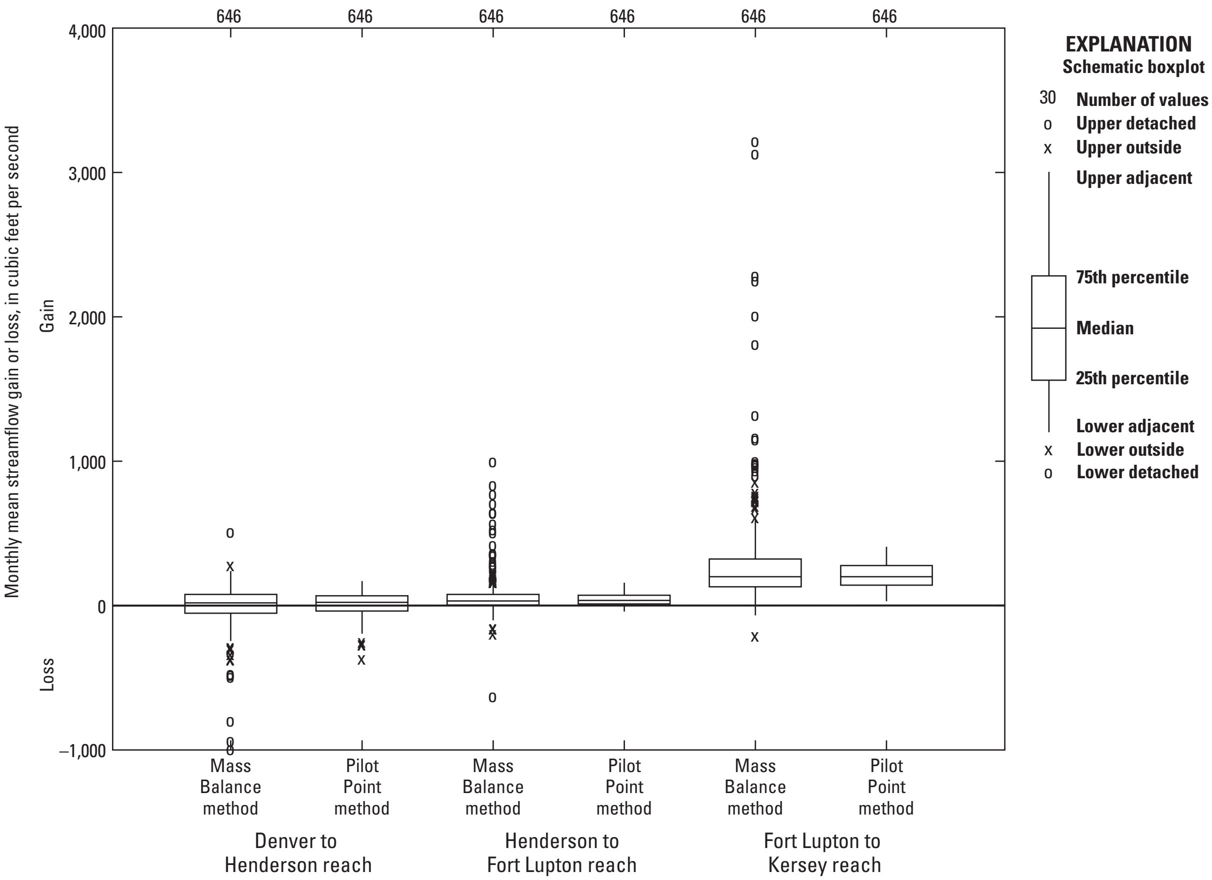


**Figure 15.** Boxplots comparing Mass Balance and Pilot Point estimates of monthly mean streamflow gains and losses for South Platte River study reaches, Colorado.

more consistent with a conceptual model of groundwater flow being gradual and slow. The Pilot Point results provide a better fit to this conceptual model of groundwater flow.

The Pilot Point method limits extreme values by utilizing maximum gain and loss constraints. The Mass Balance method has no such inherent constraints. The selection of parameter values for calculating the Pilot Point constraints is subject to some degree of professional judgment. If properly calculated and applied, the constraints do represent reasonably objective methods, which are based on sound principles of groundwater hydraulics, for constraining extreme values from the mass-balance estimates.

The smoothing applied to the Pilot Point results is a function of the bin width, where the bin width is the length of time expressed in days, over which the results are averaged for the computation of a moving average. For the Mass Balance method, monthly rather than daily mean base flow data were used to provide some degree of smoothing. For this study, a bin width of 61 days was selected for the Pilot Point method based on its use in another study (Ray Bennett, Colorado Division of Water Resources, written commun., 2003) and the reasonable nature of the results it produced for that study.

# Summary

The U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board, compared two methods for estimating base flow in three reaches of the South Platte River between Denver and Kersey, Colorado. The three stream reaches are from Denver to Henderson, Henderson to Fort Lupton, and Fort Lupton to Kersey, Colorado. The two methods utilized in this study are the Mass Balance and the Pilot Point methods. Both methods are based on mass balances of streamflow in a given reach, using historical measurements of all known inflow to and outflow from the stream. Estimates computed by the two methods were based upon a 54-year period of record (1950 to 2003).

The Mass Balance method for estimating base flow is based on a mass balance of all inflows to and outflows from a given stream reach, with the equation being solved for groundwater flow into or out of the reach. A positive mass balance indicates a gaining stream (base flow), and a negative mass balance indicates a losing reach. The mass balance was calculated using daily mean measured streamflow, wastewater treatment plant discharge, and stream diversion data. The results from using daily mean flows were highly variable and are not considered to be representative of the actual occurrence of base flow as a function of the interaction of groundwater and surface water. Monthly mean base flow was calculated as the average of all daily mean mass-balance results for a given month. Monthly mean base flows were calculated to help limit some of the extreme values and smooth some of the large day-to-day variability in the daily mass-balance results.

The Pilot Point method also relies on a daily mean mass balance of all inflows into and outflows from a stream reach. The Pilot Point method differs from the Mass Balance method in that extreme daily mass-balance results are constrained utilizing two analytical solutions, Darcy's law and the Glover equation, which represent the maximum possible streamflow gain or loss, respectively. Additionally, the Pilot Point method utilizes a smoothing function, based on a moving average of the daily constrained mass-balance results. The moving average for this study utilized a period, or bin width, of 61 days. By design, the maximum gain and loss constraints and the smoothing function are utilized to provide base-flow estimates that exhibit reasonable maximum values and day-to-day and month-to-month variability that are consistent with the concept of groundwater flow being gradual and slow.

In the Denver to Henderson reach, the median annual mean base-flow estimate was 34.0 cubic feet per second ($ft^3/s$) using the Mass Balance method and 39.1 $ft^3/s$ using the Pilot Point method. Expressed as streamflow gain per river mile, the Mass Balance estimate of annual mean base flow was 2.2 cubic feet per second per mile ($ft^3/s/mi$) and the Pilot Point estimate was 2.5 $ft^3/s/mi$. In the Henderson to Fort Lupton reach, the median annual mean base-flow estimate was 50.0 $ft^3/s$ using the Mass Balance method and 40.0 $ft^3/s$ using the Pilot Point method. Expressed as streamflow gain per river mile, the Mass Balance estimate of annual mean base flow was 3.1 $ft^3/s/mi$ and the Pilot Point estimate was 2.5 $ft^3/s/mi$. In the Fort Lupton to Kersey reach, the median annual mean base-flow estimate was 234 $ft^3/s$ using the Mass Balance method and 214 $ft^3/s$ using the Pilot Point method. Expressed as streamflow gain per river mile, the Mass Balance estimate of annual mean base flow was 6.4 $ft^3/s/mi$ and the Pilot Point estimate was 5.8 $ft^3/s/mi$.

Both the Mass Balance and Pilot Point results provided similar temporal patterns in annual and monthly base flow. Seasonal patterns in estimated base flow were similar for both methods. This degree of similarity between the two methods was expected because both methods are based on a streamflow mass balance. The magnitudes of estimates provided by the two methods were measurably different. The Mass Balance method provided estimates of gains and losses that were more variable and of larger magnitude than those provided by the Pilot Point method.

The daily and monthly Mass Balance results were rather variable to the point that they appeared extreme with respect to the concept of groundwater flow as being gradual and slow. The large degree of variability in the day-to-day and month-to-month Mass Balance results is likely the result of factors other than streamflow gains from or losses to the alluvial aquifer. These factors could include ungaged stream inflows or outflows, short-term streamflow losses to and gains from temporary bank storage, and any lag in streamflow accounting owing to lag time of flow within a reach. Less day-to-day variability, smaller-magnitude extreme values, and smoother transitions in base-flow estimates provided by the Pilot Point method are more consistent with a conceptual model of groundwater flow being gradual and slow. The combination of extreme value constraints and a smoothing technique in the Pilot Point method had a more profound dampening effect on results compared to the Mass Balance method, in which monthly rather than daily mean base-flow data were used to provide some degree of smoothing. The Pilot Point method provided a better fit to the conceptual model of groundwater flow and appeared to provide reasonable estimates of base flow.

## Selected References

Arnold, L.R., Mladinich, C.S., Langer, W.H., and Daniels, J.S., 2010, Land-use analysis and simulated effects of land-use change and aggregate mining on groundwater flow in the South Platte River valley, Brighton to Fort Lupton, Colorado: U.S. Geological Survey Scientific Investigations Report 2010–5019, 117 p.

Brodie, R.S., and Hostetler, S., 2005, A review of techniques for analysing base flow from stream hydrographs: Proceedings of the NZHS-IAH-NZSSS 2005 Conference, 28 Nov–2 Dec, 2005, Auckland, New Zealand, [*http://adl.brs.gov.au/brsShop/data/iah05_base flow_final.pdf*; accessed August 20, 2010]

Camp, Dresser, & McKee, Inc., 1994, South Platte River Segment 15 Water Quality—A historical perspective: [*http://www.metrowastewater.com/documents/segment15.pdf*; accessed August 10, 2010].

Carpenter, L.G., 1916, Seepage and return water: Colorado Agricultural Experimentation Station Bulletin 180, part 1, 70 p.

Darcy, H., 1856, Les fontaines publiques de la ville de Dijon: Paris, Victor Dalmont, 647 p.

Frank, Steve, 2009, A 45-year history—Metro Wastewater Reclamation District: Denver, Colo., Metro Wastewater Reclamation District, 353 p.

Glover, R.E., 1978, Transient ground water hydraulics: Fort Collins, Colo., Water Resources Publications, second printing, 413 p.

Griffiths, G.A., and Clausen, B., 1997, Streamflow recessions in basins with multiple water storages: Journal of Hydrology, v. 190, p. 60–74.

Hall, F.R., 1968, Base-flow recessions—A review: Water Resources Research, v. 4, no. 5, p. 973–983.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier, Studies in Environmental Science 49, 529 p.

Hurr, R.T., and Schneider, P.A., Jr., and others, 1972a, Hydrogeologic characteristics of the valley-fill aquifer in the Brighton reach of the South Platte River valley, Colorado: U.S. Geological Survey Open-File Report 72–332, 2 p., 6 pls.

Hurr, R.T., and Schneider, P.A., Jr., and others, 1972b, Hydrogeologic characteristics of the valley-fill aquifer in the Greeley reach of the South Platte River valley, Colorado: U.S. Geological Survey Open-File Report 73–124, 2 p., 6 pls.

Institute of Hydrology, 1980, Low flow studies: Wallingford, Oxon, United Kingdom, report no. 1, 21 p.

Johnson, A.I., 1967, Specific yield—Compilation of specific yields for various materials: U.S. Geological Survey Water-Supply Paper 1662–D, 74 p.

Litke, D.W., and Appel, C.L., 1989, Estimated use of water in Colorado, 1985: U.S. Geological Survey Water-Resources Investigations Report 88–4101, 157 p.

McMahon, P.B., Lull, K.J., Dennehy, K.F., and Collins, J.A., 1995, Quantity and quality of groundwater discharge to the South Platte River, Denver to Fort Lupton, Colorado, August 1992 through July 1993: U.S. Geological Survey Water-Resources Investigations Report 95–4110, 71 p.

Minges, D.R., 1982, Selected hydrologic characteristics of the South Platte River in the vicinity of the proposed Narrows Reservoir near Fort Morgan, Colorado: U.S. Geological Survey Water-Resources Investigations Report 82–4071, 25 p.

Nathan, R.J., and McMahon, T.A., 1990, Evaluation of automated techniques for base flow and recession analyses: Water Resources Research, v. 26, no. 7, p. 1465–1473.

Parshall, R.L., 1922, Return of seepage water to the lower South Platte River in Colorado: Fort Collins, Colo., Colorado Agricultural Experiment Station Bulletin 279, 72 p.

Robson, S.G., 1987, Bedrock aquifers in the Denver Basin, Colorado—A quantitative water-resources appraisal: U.S. Geological Survey Professional Paper 1257, 73 p.

Robson, S.G., 1996, Geohydrology of the shallow aquifers in the Denver metropolitan area, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA–736, 5 sheets, scale 1:50,000.

Robson, S.G., Arnold, L.R., and Heiny, J.S., 2000, Geohydrology of the shallow aquifers in the Greeley-Nunn area, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA–746–A, 5 sheets, scale 1:50,000.

Robson, S.G., Heiny, J.S., and Arnold, L.R., 2000, Geohydrology of the shallow aquifers in the Fort Lupton-Gilcrest Area, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA–746–C, 5 sheets, scale 1:50,000.

Ruddy, B.C., 1984, Streamflow gain-and-loss and suspended-sediment characteristics of the South Platte River and three irrigation canals near Fort Morgan, Colorado: U.S. Geological Survey Water-Resources Investigations Report 84–4220, 82 p.

Smakhtin, V.U., 2001, Low flow hydrology—A review: Journal of Hydrology, v. 240, p. 146–186.

State of Colorado, 2007, HydroBase data available on the World Wide Web: accessed February 2007, at *http://cdss.state.co.us/docs/?category=53&basin=-1*.

State of Colorado, 2008, Straightline diagram of South Platte River, Water District 2, accessed December 21, 2010, at *ftp://dwrftp.state.co.us/cdss/ovw/sf/District2_Straightline_20081008.pdf*.

Tallaksen, L.M., 1995, A review of baseflow recession analysis: Journal of Hydrology, v. 165, p. 349–370.

U.S. Geological Survey, 2007, National Water Information System (NWISWeb) data available on the World Wide Web: accessed February 2007 at *http://waterdata.usgs.gov/co/nwis*.

U.S. Environmental Protection Agency, 2010, Water discharge permits (PCS) database: U.S. Environmental Protection Agency water discharge permit records [*http://www.epa.gov/enviro/html/pcs/pcs_query.html*; accessed May 26, 2010].

Wilson, W.W., 1965, Pumping tests in Colorado: Denver, Colorado Water Conservation Board Groundwater Circular 11, 361 p.

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